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Investigation of polar and azimuthal distributions of subthreshold pions at intermediate energies

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Abstract

We present data on π^0 emission coincident with projectile-like fragments from $^{36}Ar+{}^{197}Au$ and $^{36}Ar+{}^{12}C$ reactions at 95 MeV/u. The pion polar and azimuthal distributions, obtained for different impact parameters, are interpreted in terms of strong final-state interactions. We propose to exploit pion shadowing as a probe of the competition between attractive and repulsive forces in nucleus–nucleus collisions.

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Whereas a wealth of knowledge has been accumulated over the past decades on the interactions of charged pions with nuclei, the situation is radically different for neutral pions, of which no secondary beams are available. Only recently quantitative information on π^0-nucleus interactions has been deduced from a study of pion reabsorption effects in the systematics of heavy-ion subthreshold π^0 production cross sections [1] and from pion energy spectra [2]. These final-state interactions do also strongly manifest themselves in the pion angular distributions, as discussed first by Stachel et al. [3] and Grosse [4], and they have to be taken into account in a consistent interpretation of pion production in heavy-ion reactions. In this letter we present exclusive data of subthreshold π^0 emission in peripheral heavy-ion collisions from an experiment performed at GANIL. Neutral pions have been observed with the TAPS photon spectrometer [5] in coincidence with projectile-like fragments, detected in the GANIL magnetic spectrograph SPEG. Polar and azimuthal distributions have been measured, and are interpreted in terms of an interplay between the π^0 source dynamics and pion reabsorption effects.

An important aspect of reaction dynamics at intermediate energies deals with the competition between the attractive nuclear mean field, on the one hand, and repulsive Coulomb and compressional forces on the other. We propose a novel approach to determine directly the sign of deflection of projectile-like fragments in asymmetric heavy-ion collisions, namely via a measurement of shadowing effects in the pion azimuthal distributions.

Data were taken for the reactions $^{36}Ar + ^{197}Au$ and $^{36}Ar + ^{12}C$ at a beam energy of 95 MeV/u, irradiating gold targets of 20 mg/cm^2 and C targets of 15 mg/cm^2. Photons were registered in 5 TAPS blocks of 64 BaF_2 scintillators each, placed in the horizontal plane at a distance of 62 cm from the target, and at polar angles of 65°, 109°, 212°, 258° and 309°, respectively. The thin plastic scintillator installed in front of each BaF_2 detector was used to veto hits from charged particles. A GEANT simulation [6] of the detector response gave for this setup an angle- and energy-integrated π^0 detection efficiency of 1.6%. The BaF_2 signals were times against the accelerator RF, yielding a FWHM time resolution of ≤ 550 ps. Finally, projectile-like fragments (PLF) were registered at 0° in the magnetic spectrograph SPEG [7], with an angular acceptance of $\pm 2.0°$, both horizontally and vertically.

In the data analysis, a clean separation of γ rays from charged particles and neutrons was achieved by requiring (i) no signal in the veto modules covering the hit BaF_2 detectors, (ii) prompt time of flight and, (iii) the γ pulse shape of the BaF_2 signals. For each photon hit the energies of the adjacent modules were summed to improve the overall energy resolution. Neutral pions were identified through an invariant-mass analysis of 2-photon events, yielding a FWHM resolution of the π^0 peak of 13%.

With the SPEG magnetic field set at 93.5% of the beam rigidity, we obtain PLF charge and mass resolutions of respectively 0.6 and 0.2 units FWHM (see Fig. 1). The PLF FWHM angular resolution was determined to be 0.2° horizontally and 0.5° vertically, i.e. sufficiently good for characterizing the scattering plane of fragments deflected at angles $> 0.5°$ with respect to the beam axis. In the further analysis, events with $0.5° < \theta_{PLF} < 2.0°$ have been accepted, corresponding

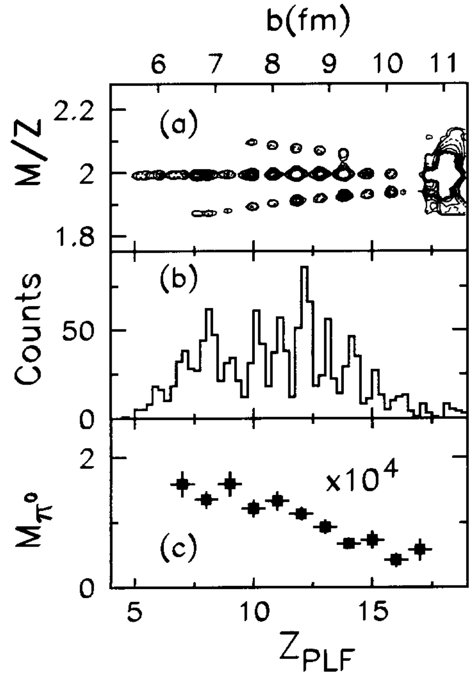

Fig. 1. (a) PLF mass versus charge distribution measured at 0° for 95 MeV/u $^{36}Ar + ^{197}Au$. (b) Distribution of PLF's detected in coincidence with neutral pions. (c) π^0 multiplicity versus PLF charge; error bars are statistical. The PLF charge has not been corrected for evaporated light charged particles. An impact parameter scale based on abrasion–ablation calculations [8] is shown on the top.

to a solid angle of 3.6 msr and leading to a large geometric coverage of the strongly forward-peaked PLF yield. We have used the charge $Z_{\rm PLF}$ as a measure of centrality and the correlation with impact parameter b has been established through an abrasion–ablation calculation [8], which yielded an estimated spread Δb of 1.5–2.5 fm. The neutral-pion multiplicity as a function of the PLF charge is shown in Fig. 1c for ^{36}Ar on ^{197}Au collisions: starting out at $Z_{\rm PLF}=17$, corresponding to grazing impact parameters ($b\simeq 11$ fm), π^0 production rises from zero up to close to its saturation value, at maximum overlap of the Ar and Au nuclei ($b\leq 5$ fm). Unlike previous exclusive measurements where b was selected via the fission-fragment folding angle [9] or through cuts on light charged-particle multiplicities [10], our data also demonstrate pion emission in the most peripheral collisions.

Inclusive π^0 polar distributions, corrected for the energy- and angle-dependent detector response, and transformed into the N–N cm frame (with $\beta_{NN}=0.22$), are shown in Fig. 2a; a pronounced forward–backward asymmetry is clearly apparent for both systems. In the laboratory frame the polar distribution is determined by three effects: (i) the intrinsic angular distribution from the elementary production process, with a $\mathrm{d}\sigma/\mathrm{d}\Omega=a+b\cos^2\theta$ shape in the N–N frame (see e.g. Ref. [11]); superimposed on this (ii) the source-frame motion and finally (iii) a distortion from pion absorption and scattering. The pion final-state interactions prohibit a straightforward moving-source analysis, as can be done for photons, and make it impossible to extract a source velocity directly. However, in very peripheral events, the particular geometry of the collision (the two nuclei are side by side) removes the forward–backward asymmetry due to shadowing and restores a symmetric polar distribution in the source frame. A selection of fragments with $Z_{\rm PLF}=14$–17 samples impact parameters in Ar+Au (Ar+C) collisions larger than 9 fm (4 fm). Pion polar distributions coincident with these PLF's are shown in Fig. 2b: they are indeed symmetric in the N–N cm frame, confirming a source velocity of $\beta_S=\beta_{NN}=0.22$ (in contrast to 0.07 for the Ar+Au cm frame, and 0.32 for the Ar+C frame). This result clearly supports the picture of pion generation in mostly first-chance N–N collisions.

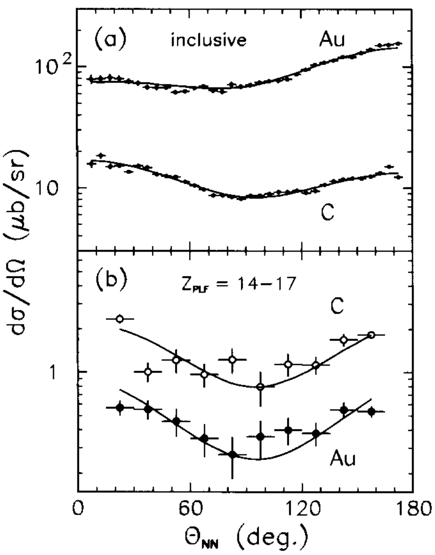

Fig. 2. (a) Inclusive π^0 polar distribution measured for ^{36}Ar + ^{197}Au and ^{36}Ar + ^{12}C at 95 MeV/u, transformed into the N–N cm frame. (b) same as (a), but for very peripheral collisions, selected by requiring $Z_{\rm PLF}$ in the range 14–17. The solid curves are shadowing calculations normalized to the integral of the data (see text for details).

To quantify the π^0 final-state interactions, we have performed shadowing calculations on the basis of a simple geometric model in which the pions are emitted uniformly from a mid-rapidity source formed by the overlap region of the two colliding nuclei; details are given in Ref. [1]. In this model, pion absorption is characterized by an absorption length $\lambda_{\rm ABS}$, averaged over the pion kinetic energy spectrum, and the N–N cm intrinsic π^0 angular distribution is described by a Legendre polynomial expansion $\mathrm{d}\sigma/\mathrm{d}\Omega=A_0[1+a_2P_2(\cos\theta)$. A simultaneous fit to the Ar+Au and Ar+C inclusive polar distributions yields $\lambda_{\rm ABS}=5.7\pm0.5$ fm and $A_2=0.40\pm0.05$. With this set of parameters a very good description of both the inclusive and peripheral π^0 distributions is achieved (see Fig. 2), confirming the mid-rapidity nature of the pion source. The present value of $\lambda_{\rm ABS}$ is very close to the 5.5 fm determined previously from a systematic study [1] of inclusive π^0 production cross sections measured at beam energies around 40 MeV/u. Despite the energy dependence of $\lambda_{\rm ABS}$ this similarity is not surprising, as the pion kinetic energy distributions are known to depend only weakly on bombarding energy below $\simeq 150$ MeV/u [12], with typical values of $\langle E_{\rm kin}\rangle\simeq 30$–40 MeV in the N–N cm system.

For peripheral collisions leading to finite scattering

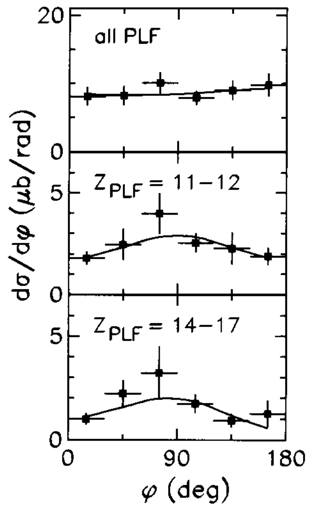

Fig. 3. π^0 azimuthal distributions in ^{36}Ar + ^{197}Au (with $36° < \theta_{CM} < 162°$) for different cuts on Z_{PLF}. In order to improve statistics, the two halves of the distribution (0°–180° and 180°–360°) have been added. The solid lines represent a cosine expansion fitted to the data (see text and Table 1).

angles an event plane φ_0 can be defined, using the beam direction and the PLF momentum vector measured in SPEG, and the π^0 azimuthal distribution $d\sigma/d\varphi$ can be plotted with respect to this plane. The accuracy of φ_0 is limited by particle evaporation from the excited PLF, instrumental resolution, and, to a much lesser extent, multiple scattering in the target. From a simulation these effects are estimated to result in a spread of $\Delta\varphi_0 \leq 40°$ FWHM for $Z_{PLF} \geq 10$. It is not clear to what extent a contribution to $\Delta\varphi_0$ from the Fermi-momentum kick of the abraded nucleons has to be considered, because, if pion production and abrasion are concurrent processes, pion propagation is partly subsequent and senses the out-going spectator fragments. Our analysis shows indeed (see Fig. 3) that the azimuthal distribution of neutral pions is almost flat, if all PLF's are allowed, but if PLF charges in the range 14–17 (11–12) are selected, corresponding to peripheral (semi-peripheral) collisions, a strong azimuthal anisotropy developes. A cosine expansion $d\sigma/d\varphi = N(1 + S_1 \cos\varphi + S_2 \cos 2\varphi)$ fitted to the π^0 yield as function of the azimuthal angle φ, with parameters listed in Table 1, shows that the emission is enhanced by a factor $\simeq 1.7$–2.6 around $\varphi = 90°$, that is perpendicular to the reaction plane; in-plane the projectile and target spectator matter introduce shadowing due to strong pion reabsorption. Conversely, in Ar + C we see no out-of-plane enhancement presumably because in this very light system the PLF momentum vector does not define a good event plane. Pion azimuthal anisotropies have been observed in 1 GeV/u Au + Au collisions too [13,14] and have likewise been attributed to final-state interactions [15,16]. It is however interesting to note that at these much higher bombarding energies both experiment and theory find sizeable anisotropies only for pion transverse momenta $p_t > 200$ MeV/c, i.e. quite in contrast to the situation discussed here, where the effect is strong, despite the low momenta ($p < 200$ MeV/c) of the produced pions.

Within the shadowing picture one expects for an asymmetric collision system, besides the out-of-plane enhancement, a 0°/180° asymmetry in the pion azimuthal distributions, with $\varphi = 0°$ defined as pion emission towards the projectile side and $\varphi = 180°$ towards the target side, respectively. In the case of e.g. Ar + Au, the pion yield should indeed be *larger* on the projectile side (the smaller of the two nuclei), if there is *positive*, i.e. repulsive deflection (near-side collision), and *smaller*, if the deflection is to *negative* angles, i.e. if it is attractive (far-side collision). Sensitivity to such an asymmetry is described by the parameter S_1 of the cosine fit to $d\sigma/d\varphi$. For the most peripheral event selection ($Z_{PLF} = 14$–17), S_1 is 0.21 (see Table 1), corre-

Table 1
Parameters from a cosine expansion fitted to the π^0 azimuthal distributions measured in ^{36}Ar + ^{197}Au collisions for different cuts on Z_{PLF}

Z_{PLF}	Counts	S_1	S_2	χ^2/NDF	R
all	1094	-0.05 ± 0.06	0.02 ± 0.09	0.59	$0.96^{-0.16}_{+0.19}$
11–12	303	0.00 ± 0.02	-0.25 ± 0.11	0.58	$1.67^{-0.34}_{+0.45}$
14–17	178	0.21 ± 0.18	-0.45 ± 0.19	1.26	$2.64^{-0.94}_{+1.92}$

The total number of counts in the fitted spectra is also given, as well as the out-of-plane ratio $R = (1 - S_2)/(1 + S_2)$.

sponding at a confidence level of 85% to a larger yield at $\varphi = 0°$ and thus repulsive deflection. For semi-peripheral events ($Z_{PLF} = 11$–12), however, we find $S_1 = 0$, i.e. consistent with symmetric yields.

According to theoretical expectations [17–20], in central heavy-ion collisions repulsive and attractive forces balance each other at bombarding energies around 50–150 MeV/u, with the repulsive part of the nuclear potential becoming dominant at energies above the so-called valence energy E_{bal}. Likewise, at a given bombarding energy, one has an evolution of the interplay of forces with impact parameter. One should note that the usual experimental method applied to the study of E_{bal}, namely through a measurement of nuclear-matter flow [21–24] is not sensitive to the sign of the deflection angle, which is inferred from theoretical arguments only. In principle, near-side and far-side deflections can be distinguished from a γ-ray circular polarization measurement and this technique has been applied in the past to the study of dissipative processes [25,26], as well as projectile fragmentation [27]. The interpretation of the polarization signal however depends strongly on the mechanism of angular-momentum transfer involved and is consequently highly model-dependent. Pion shadowing could offer here a more direct approach, as demonstrated by the azimuthal asymmetries (S_1) observed in our data. The latter are indeed consistent with the following scenario: whereas repulsive Coulomb forces dominate at very large impact parameters, in the less peripheral collisions the attractive mean field starts to take over. Apparently, at beam energies around 100 MeV/u, compression is not yet strong enough to ensure repulsion also in semi-peripheral collisions. However, better experimental statistics, as well as a comparison with realistic dynamical calculations would be necessary to more quantitatively assess the actual sensitivity of this new probe of the force balance in nuclear reactions.

In summary, we have measured inclusive and exclusive π^0 production in the reactions $^{36}Ar + ^{197}Au$ and $^{36}Ar + ^{12}C$ at 95 MeV/u. Within the framework of a geometric shadowing calculation, the π^0 polar distributions can be described in terms of a mid-rapidity source, in combination with strong final-state effects. A prominent enhancement perpendicular to the reaction plane has been observed for large impact parameters and has been interpreted as yet another manifestation of the π^0 final-state interactions. Taking advantage of the 0°/180° azimuthal asymmetries, we finally propose a novel way to investigate the balance between attractive and repulsive deflection in peripheral and semi-peripheral intermediate-energy nucleus–nucleus collisions.

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